

Deployment strategy for battery energy storage system in distribution network based on voltage violation regulation

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Abstract. In order to improve the situation of voltage violation caused by the grid-connection of photovoltaic (PV) system in a distribution network, a bi-level programming model is proposed for battery energy storage system (BESS) deployment. The objective function of inner level programming is to minimize voltage violation, with the power of PV and BESS as the variables. The objective function of outer level programming is to minimize the comprehensive function originated from inner layer programming and all the BESS operating parameters, with the capacity and rated power of BESS as the variables. The differential evolution (DE) algorithm is applied to solve the model. Based on distribution network operation scenarios with photovoltaic generation under multiple alternative output modes, the simulation results of IEEE 33-bus system prove that the deployment strategy of BESS proposed in this paper is well adapted to voltage violation regulation invariable distribution network operation scenarios. It contributes to regulating voltage violation in distribution network, as well as to improve the utilization of PV systems.

1. Introduction

With growing trends in distributed photovoltaic (PV) system installations in the distribution network, the structural characteristics of traditional radiation distribution network have been changed. And it makes the voltage of the node change with the direction of the power flow, which usually leads to the situation of voltage violation. Therefore, it is necessary to regulate grid voltage more flexibly.

In order to address the voltage rise issue in distribution network caused by high penetration of distributed PV systems, various methods have been proposed. Using larger transformers and conductors to upgrade the existing distribution network is a straightforward but expensive approach [1,2]. Meanwhile, adjusting the load tap changer (LTC) positions of transformers is another way to regulate voltage in distribution network [3,4].

In addition to using transformers and conductors, real-time power control is also an effective way to manage voltage profiles in distribution networks. In [5], a new real-time power capping method for overvoltage regulation is proposed. In order to maintain voltage below a pre-set upper limit, the method is effective by maximizing the PV power output and allocating the real power curtailments among all the PV systems equally in the network.

PV and battery energy storage system (BESS) are capable of voltage regulation due to their active and reactive power regulation ability. In [6], a new strategy to achieve voltage regulation in distributed



network with PV and BESS is proposed. The proposed method employs the network impedance matrix to obtain the solution of optimal sizing and allocation of BESS rather than use recursive algorithms.

When dealing with BESS deployment problem based on voltage violation regulation, the coordinated power control of PV and BESS are needed to be solved. Therefore, it is difficult to obtain the satisfactory solution when the model includes the coordinated power control of PV and BESS and the BESS deployment.

In this paper, a bi-level programming model is proposed for BESS deployment in the distribution network with PVs, so as to realize flexible voltage regulation. The questions how distribution network with PV under multiple output modes influence configuration of BESS and the coordination of PV and BESS are researched on. The rest of this paper is arranged as follows: in Section 2, a BESS deployment model based on bi-level programming is established. In Section 3, the solution to solve the mathematics model is presented. In Section 3.1, power control coordination is presented. In Section 3.2, augmented objective function and flow chart for solving this bi-level programming model are presented. Case study and results are demonstrated in Section 4, and finally, conclusions are drawn in Section 5.

2. Bi-level BESS optimal deployment model

To research on the BESS deployment in the distribution network with PV, bi-level programming model is established including inner optimization model and outer optimization model. Through inner optimization we get voltage violation bounds, then the voltage violation bounds are taken into consideration while we are seeking for optimal size and location of BESS. Therefore, via bi-level programming model which is effective in solving multi-goals programming problems, we can realize optimal size and allocation of BESS as well as voltage violation regulation simultaneously.

2.1. Inner optimization model

The active power and reactive power of PV and BESS are considered as variables which can be controlled to relieve voltage violation in the distribution network. The objective function of voltage violation regulation is

$$\min f_1 = \sum_{t=1}^T \sum_{i=1}^I g(V_{i,t}) \quad (1)$$

where, $V_{i,t}$ denotes the voltage of i^{th} node at time t ; I is the number of nodes except the slack node; T is the total number of the periods in a whole day; $g(V_{i,t})$ denotes the function of voltage violation, which is demonstrated as follows

$$y(V_i) = \frac{1}{\sigma\sqrt{2\pi}} (1 - e^{-\frac{(V_i - \mu)^2}{2\sigma^2}}) \quad (2)$$

$$g(V_i) = \begin{cases} \omega_v \cdot (V_i - V_0)^2 & V_i \leq V_{hl} \text{ or } V_i \geq V_{hu} \\ y(V_i) - y(V_{sl}) & V_{hl} < V_i < V_{sl} \\ y(V_i) - y(V_{su}) & V_{su} < V_i < V_{hu} \\ 0 & V_{sl} \leq V_i \leq V_{su} \end{cases} \quad (3)$$

where, μ and σ are the mean and standard deviation of Gaussian function respectively; $y(V_i)$ is the function obeying Gaussian function to describe the voltage violation; V_{sl} and V_{su} are the lower and upper soft bounds of node voltage respectively; V_{hl} and V_{hu} are the lower and upper hard bounds of node voltage respectively; V_0 is the rated voltage of node voltage; ω_v is the penalty factor of the

hard voltage constraint, and it is usually set as a large positive number, e.g. 20000.

In order to minimize the active power fluctuation, two objective functions are established, which are shown in (4) and (5).

$$\min f_2 = \tau \sum_{t=1}^T \sum_{s=1}^S |P_{s,t}| \quad (4)$$

$$\min f_3 = \sum_{t=1}^T \tau \left(\sum_{l=1}^L P_{l,t} + \sum_{j=1}^J (P_{MPP,j,t} - P_{j,t}) \right) \quad (5)$$

where, τ denotes the length of time period, $P_{s,t}$ is the charging and discharging power of s^{th} BESS at time t , S is the total number of BESS, $P_{l,t}$ is the active power loss of the l^{th} line at time t , L is the number of the lines, $P_{MPP,j,t}$ and $P_{j,t}$ is the maximum active power and the actual active power of the j^{th} PV at time t respectively, and J is the number of PV.

The objective function (4) is to minimize the operation of BESS so as to reduce the power loss, function (5) is to minimize the PV energy curtailment. Constraint conditions of these two objective functions are demonstrated as follows

$$\begin{cases} V_{hl} \leq V_i \leq V_{hu} \\ 0 \leq |P_s| \leq P_{r,s} \\ -Q_{lb,s} \leq Q_s \leq Q_{ub,s} \\ -\sqrt{P_{r,s}^2 - P_s^2} \leq Q_s \leq \sqrt{P_{r,s}^2 - P_s^2} \\ S_{OC,lb} \leq S_{OC,t} - \frac{\eta_s \cdot P_s \cdot \tau}{C_{r,s}} \leq S_{OC,ub} \\ S_{OC,0} - S_{OC,T} = 0 \\ -Q_{lb,j} \leq Q_j \leq Q_{ub,j} \\ \sqrt{Q_j^2 + P_j^2} \leq S_j \end{cases} \quad (6)$$

where, P_s and Q_s are the active power and reactive power of the s^{th} BESS respectively; $P_{r,s}$ denotes the rated power of the s^{th} BESS; $Q_{lb,s}$ and $Q_{ub,s}$ are the maximum capacitive reactive power and maximum inductive reactive power of the s^{th} BESS respectively; $S_{OC,t}$ is the state of charge of the s^{th} BESS at time t ; η_s is the charging/discharging efficiency of the s^{th} BESS; $C_{r,s}$ is the rated capacity of the s^{th} BESS; $S_{OC,lb}$ and $S_{OC,ub}$ are the lower and upper limits of SOC of the s^{th} BESS; P_j and Q_j are the active power and reactive power of the j^{th} PV respectively; S_j indicates the rated capacity of the j^{th} PV; while PV is under the restricted reactive power output model, $Q_{lb,j}$ and $Q_{ub,j}$ are the maximum capacitive reactive power and maximum inductive reactive power of the j^{th} PV respectively.

2.2. Outer optimization model

In order to achieve economic deployment of BESS, both minimal total rated capacity and power of BESS should be considered in objective functions. The outer optimization model is formulated as follows

$$\min h_1 = \sum_{k=1}^K n_k F_k(f_1, f_2, f_3) \quad (7)$$

$$\min \quad h_2 = \sum_{s=1}^S C_{r,s} \quad (8)$$

$$\min \quad h_3 = \sum_{s=1}^S P_{r,s} \quad (9)$$

$$\begin{aligned} \text{s.t.} \quad & \sum_{s=1}^S C_{r,s} \leq C_{r,ub} \\ & \sum_{s=1}^S P_{r,s} \leq P_{r,ub} \\ & P_{r,s} \leq c_{PC} \cdot C_{r,s} \end{aligned} \quad (10)$$

where, n_k is the number of days which is similar to the typical day k in a year; K is the number of kinds of typical days; F_k is the function concerning equation (1), (4) and (5), the specific expression of which is demonstrated in (12); $C_{r,ub}$ and $P_{r,ub}$ are the upper limit of the total capacity and power of BESS respectively; c_{PC} is the typical proportional coefficient between $C_{r,s}$ and $P_{r,s}$.

3. Application and solution for the BESS deployment model

3.1. Power control coordination

To realize coordinated power control of PV and BESS, several factors should be taken into consideration as the control variables

- The active power of the PV;
- The reactive power of the PV;
- The active power of the BESS;
- The reactive power of the BESS.

3.2. Augmented objective function

In order to turn the inner and outer optimization model into a single objective optimization model respectively, augmented objective functions of inner and outer optimization model are established in section 3.2.1 and section 3.2.2. The flow chart for solving the bi-level programming model is presented in section 3.2.3.

3.2.1. Augmented objective function of the inner optimization model. In order to observe the power control principles, the augmented objective function of inner optimization model is as follow

$$\min \quad H_{in} = g_{1,k} + p_{1,k} \quad (11)$$

$$p_{1,k} = f_{1,k} \quad (12)$$

$$g_{1,k} = \frac{c_1}{1 + e^{-\log(\varepsilon + f_{1,k})}} + \frac{c_2}{1 + e^{-\log(\varepsilon + f_{2,k})}} + \frac{c_3}{1 + e^{-\log(\varepsilon + f_{3,k})}} \quad (13)$$

where, ε is a small positive variables; $f_{1,k}$, $f_{2,k}$ and $f_{3,k}$ are functions presented in equations (1), (4) and (5) on typical day k ; c_1 , c_2 and c_3 are the coefficients of f_1 , f_2 and f_3 respectively; $g_{1,k}$ is the specific expression of F_k concerning typical day k ; $p_{1,k}$ is the voltage penalty function on typical day k .

3.2.2. Augmented objective function of the outer optimization model. In order to turn the outer optimization model into a single objective optimization model, outer augmented objective function is as follows

$$\min H_{ex} = g_2 + p_2 \quad (14)$$

$$g_2 = h_1 \cdot \left(\frac{a_1}{1 + e^{-\log(\varepsilon + h_2)}} + \frac{a_2}{1 + e^{-\log(\varepsilon + h_3)}} \right) \quad (15)$$

$$p_2 = \sum_{k=1}^K n_k \cdot p_{1,k} \quad (16)$$

$$h_1 = \sum_{k=1}^K n_k \cdot g_{1,k} \quad (17)$$

where, $p_{1,k}$ denotes the comprehensive penalty function of the typical day k ; a_1 and a_2 are the coefficients of h_2 and h_3 .

3.2.3. Solving procedure. The differential evolution (DE) algorithm [7,8] is applied to solve the bi-level programming model. A general flow chart is illustrated in figure 1, G and N are the numbers of the generation and individuals, NG is the pre-set maximum number of the generation; NP is the total number of individuals in a generation.

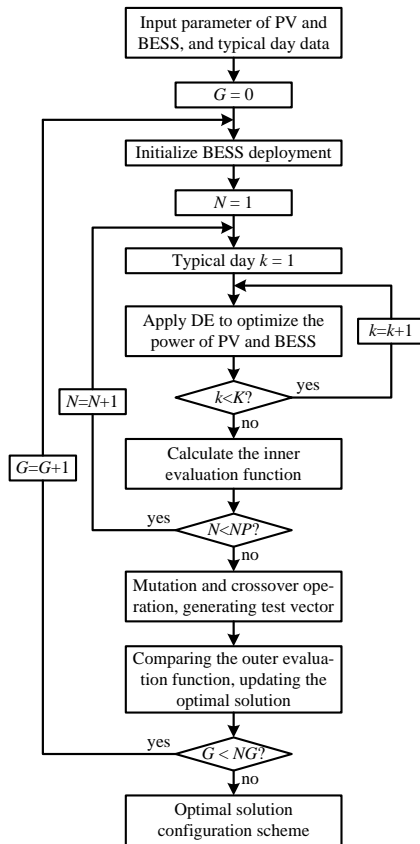


Figure 1. Flow chart for solving the BESS deployment model.

- Step 1: Input parameters of PV and BESS, and typical day data.
- Step 2: Generate the initial BESS deployment scheme.

- Step 3: Based on BESS deployment scheme, apply DE to optimize the power of PV and BESS in all typical days and then calculate the inner evaluation function H_{in} , which is presented in equation (11).
- Step 4: Apply DE to solve the outer optimization model. Based on the H_{in} in step 3, the outer evaluation function H_{ex} is calculated.
- Step 5: Determine whether the result satisfies convergence condition. If $G < NG$, output the configuration scheme. Otherwise, generate new configuration scheme of BESS through mutation crossover. Then go back to Step3 and repeat the process.

4. Case study

4.1. Distribution network operation scenarios

In order to test the validity of the proposed optimization model in this paper, the IEEE 33-buses distribution network is used. The single-line diagram is depicted in figure 2.

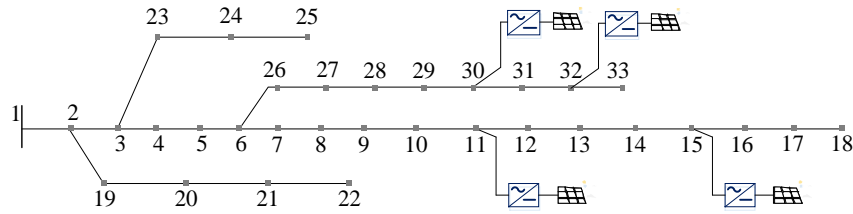


Figure 2. IEEE33-buses distribution network including distributed PV.

The rated voltage of the distribution network is 12.66 kV, and its reference capacity is 10 MVA. The nodes that PVs are connected to are 11, 15, 30 and 32, whose peak power are 0.1, 0.1, 0.1 and 0.12 p.u. respectively. The active power of PV connected to node 11 in 2 typical days is depicted in figure 3.

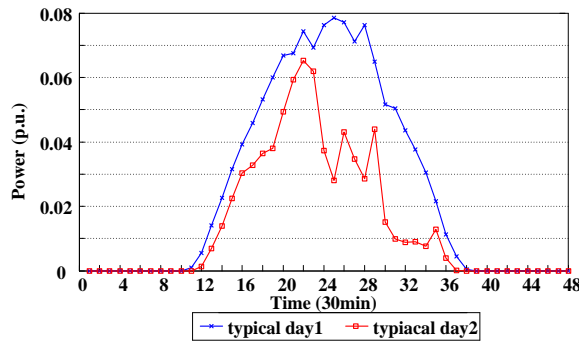


Figure 3. Curves of PV power output in two typical days.

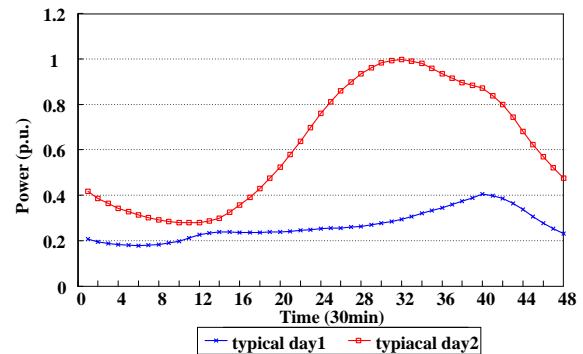


Figure 4. Normalization of load demand under operation scenarios in two typical days.

Loads of each node are depicted in figure 4. The selection of typical days depends on the time that voltage breaks the upper or the lower bound. In this case, η_s is 0.95, $SOC_0 = SOC_T = 0.4$, SOC_{lb} is 0.3 and SOC_{ub} is 0.9.

4.2. Multiple output modes of PV

Due to the different capability of reactive power output of different PV systems, there are several

power output modes for PV. Details of each mode are further explained as follows:

- **Mode 1:** Unity Power Factor.

$$Q_j = 0 \quad (18)$$

In this mode, no reactive power is generated by PV, which means the value of Q_j is always zero.

- **Mode 2:** Constant power factor.

$$Q_j = \begin{cases} P_j / \tan \varphi & P_j \leq S_j \sin \varphi \\ Q_j = 0 & P_j > S_j \sin \varphi \end{cases} \quad (19)$$

In this mode, the power factor of PV is constant, and its reactive power output is influenced by active power output. S_j is the rated power of j^{th} PV system, φ is the power factor angle. The power factor is set as 0.98 here.

- **Mode 3:** Constrained reactive power.

$$Q_{\min,j} \leq Q_j \leq Q_{\max,j} \quad (20)$$

where, $Q_{\min,j}$ and $Q_{\max,j}$ are the maximum inductive and capacitive reactive power respectively of j^{th} PV system, and they are set as $Q_{\min,j} = -0.3S_j, Q_{\max,j} = 0.3S_j$.

4.3. Results and analysis

4.3.1. Analysis of energy storage configuration scheme. The configurations of BESS in three modes of PV are listed in table 1. The computational time of processing this algorithm is around 2 hours.

Table 1. Deployment plans of BESS under basic scenarios with different PV output modes.

		Node 11	Node 15	Node 30	Node 32	sum
Mode 1	$C_r/p.u.$	0.172	0.239	0.165	0.224	0.8
	$P_r/p.u.$	0.043	0.060	0.041	0.056	0.2
Mode 2	$C_r/p.u.$	0.168	0.244	0.160	0.228	0.8
	$P_r/p.u.$	0.042	0.061	0.040	0.057	0.2
Mode 3	$C_r/p.u.$	0.147	0.265	0.149	0.240	0.801
	$P_r/p.u.$	0.036	0.066	0.037	0.060	0.199

According to table 1, the total rated capacity and rated power of BESS are about 0.8 p.u. and 0.2 p.u. respectively. The mode of the PV operation has little influence on the configuration of BESS. Despite the large load demand at night in the typical day 2, the PVs aren't able to keep voltage within reasonable range whichever mode PV operates in because photovoltaic inverter stops working when the light intensity is lower than the threshold of PV inverter at night. Thus battery energy storage systems are dispatched to adjust the voltage. Besides, according to the table 1, the rated capacity and rated power of BESS at the end of the line are larger than those of BESS in other nodes.

4.3.2. Effect of voltage regulation. In this case, $V_{hl} = 0.9$ p.u., $V_{hu} = 1.1$ p.u., $V_{sl} = 0.952$ p.u., $V_{su} = 1.048$ p.u. Time sequence distributions of maximum node voltage under typical day 1 and minimum node voltage under typical day 2 after regulation are depicted in figures 5 and 6. The dotted line in figures 5 and 6 represent the lower and upper soft bounds of node voltage respectively.

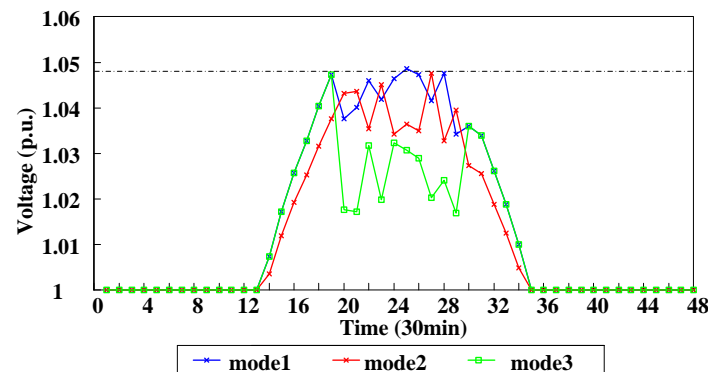


Figure 5. maximum node voltage after regulation in typical day 1.

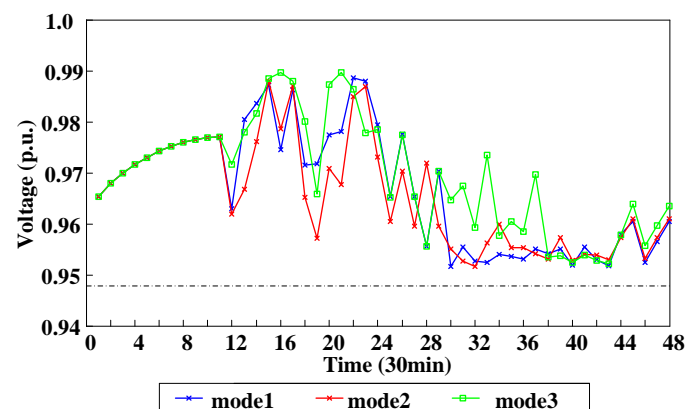


Figure 6. Minimum node voltage after regulation in typical day 2.

From figures 5 and 6 we can see that, the voltage basically meets the soft restriction under all PV output modes during the whole day after deploying BESS. Besides, the voltage always meets the hard restriction under all PV output modes during the whole day. Thus, it can be seen that the coordinated power control between PV and grid-connected BESS has a positive effect on voltage regulation.

5. Conclusions

In this paper, a bi-level programming based BESS deployment model is proposed, aiming at regulating voltage violation in the distribution network considering the coordinated power control based on both BESS and distributed PV with multi-modes. From the case study, main conclusions can be drawn as follows:

- In a typical day scenario based on different PV output modes in the distribution network, BESS deployment scheme with large capacity and large rated power at or near the end of the line is preferred, in order to diminish the voltage violation.
- The coordinated power control between grid-connected PV and BESS contributes to better effect dealing with voltage violation.

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